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Does harvesting (CPRS) mimic fire? Verifying for black spruce forests in central Québec

SFM Network Project: Comparative studies of CPRS (Cut with protection of regeneration and soils) and natural disturbance by fire: developing a basis for sustainable practices in black spruce ecosystems

by

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ABSTRACT

The primary objective of this study is to determine if the widespread practice of CPRS (cut with protection of regeneration and soils) will sustain forest ecosystem function in the black spruce forests of central Quebec. To compare the effects of CPRS and fire disturbance in these black spruce systems, permanent field plots were established in recently burned and recently harvested stands (6 - 11 years ago), and stands that were burned or harvested 56-76 years ago (12 stands total). Laboratory incubations of organic material and mineral soils from these sites indicated that CO_2-C release was related to NH_4^+-N release and that dissolved organic forms of N and P constituted a significant portion of leachates from these soils. Results from field studies in these same sites demonstrated that net N mineralization rates (15 - 20 kg/ha/yr) and labile pools of inorganic-P (55-59 mg/kg) were significantly higher in stands that were burned or harvested 56-76 years ago. There were no significant differences in soil C or nutrient stocks between the recently burned and recently harvested sites. Current field studies also suggest that there are no significant differences in soil CO_2-C efflux (1.7 - 2.1 g C m^2 d^{-1}) between the recently burned and recently harvested black spruce stands during the growing season. Current studies include the modelling of soil nutrient dynamics, identifying the effects of CPRS and fire on soil CO_2-C efflux, and an examination of how phenolic compounds affect black spruce germination in the different disturbance types.

In the six older stands, we compared stand characteristics and dynamics using stem analysis. Height growth increments after harvest were lower than those after fire. This may be due to the observed irregular structure of stands originating from mainly vegetative reproduction (layers). After harvest, individual trees showed lower biomass allocation to stem, and more allocation to branches, compared to trees originating from fire. This may be related to a more variable light regime created after harvest (more gaps). Foliar analysis of current needles indicated a tendency for reduced nutrient levels after harvest. Stand productivity was correlated with a competition index characterizing the light regime; productivity after fire was greater for equal levels of competition. Finally, the competition index was well correlated with tree nutrient status, and for the same level of competition, again, nutrient status was higher after fire compared to after harvest. There seems, then to be a relationship between the light regime, which was the result of the specific disturbance, and the site fertility. The increased presence of ericaceous shrubs noted after harvest (*Ledum groenlandicum* and *Kalmia angustifolia*) may also play a role in affecting productivity.

RÉSUMÉ

L'objectif principal de cette étude est de déterminer si la pratique de CPRS (coupe avec protection de la régénération et des sols), appliquée à grande échelle, pourra maintenir le fonctionnement des écosystèmes d'épinette noire au Québec central. Pour comparer les effets de la CPRS et de perturbation par feu dans ces écosystèmes, des parcelles permanentes ont été établies dans les peuplements perturbés récemment soit par le feu (intensité moyenne) ou par la coupe, ainsi que dans les parcelles affectées par les mêmes perturbations il y a 56-76 ans, pour un total de douze peuplements. Des incubations, au laboratoire, de la matière organique et des sols superficiels minéraux de ces sites ont indiqué que la production de CO_2 est relié à la

production de NH4+-N (azote sous forme d'ammonium) et que les formes organiques d'azote (N) et de phosphore (P) représentent des proportions importantes des éléments disponibles dans ces sols. Les résultats des études de terrain sur les mêmes stations ont démontré que les taux de minéralisation de N et les pools de P inorganique disponible ont été significativement plus élevés dans les peuplements plus âgés que dans les jeunes (6 à 10 ans), mais il n'y a pas de différence entre les deux types de perturbation. Des études en cours suggèrent également qu'il n'y a pas de différence de flux de CO_2 (1.7 - 2.1 g C m^2 d^{-1}) entre les peuplements d'épinette noire récemment brûlés et ceux qui ont été coupés, pendant la saison de croissance. Des études actuelles incluent la mesure de CO_2 pendant une deuxième saison de croissance, l'examen des effets des composantes phénoliques sur la germination de l'épinette noire suite à différentes perturbations, ainsi que la modélisation de la dynamique de l'azote.

Dans les six peuplements plus âgés, nous avons comparé les caractéristiques et la dynamique des peuplements en utilisant l'analyse des tiges. Les accroissements en hauteur après coupe ont été à la baisse, par rapport à ceux après feu. Ceci est peut-être relié à la structure irrégulière des peuplements après coupe qui se régénèrent de façon végétative, par marcottes. Après coupe, les arbres individuels démontrent moins d'allocation de la biomasse à la tige, et plus d'allocation aux branches, lorsque comparés aux arbres qui poussent après feu. Une fois de plus, ce phénomène est possiblement relié au régime de lumière plus variable existant après coupe (plus de trouées évidentes). L'analyse de feuillage d'épinette noire a indiqué une tendance vers une diminution des niveaux des éléments nutritifs après coupe. La productivité des peuplements a été corrélée à un indice de compétition qui caractérise le régime de lumière; pour des niveaux égaux de compétition, la productivité après feu a été plus élevée. L'indice de compétition a été corrélé au statut nutritif des arbres, et ici encore, pour un même niveau de compétition, le statut nutritif a été meilleur après feu qu' après coupe. On semble observer une relation entre les régimes de lumière créés par les différentes perturbations et la fertilité des stations. La présence plus importante des éricacées observée après coupe (*Ledum groenlandicum* et *Kalmia angustifolia*) pourrait aussi jouer un rôle en affectant la productivité des stations.

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INTRODUCTION

The North American boreal forest spans the width of the continent, and one of the most widespread vegetation types is the black spruce (*Picea mariana* (Mill.) BSP) – feathermoss community. In Quebec, 28% of the land area is occupied by these black spruce dominated forests that extend from the tree line as far south as 48 N (Bergeron et al. 1996). Clearly, these forests have great economic and ecological importance to this region. In central Quebec, black spruce - feathermoss communities are found on all aspects and slope positions, in contrast to western Canada and Alaska, where pure stands grow on northern slopes or on humid sites that are frequently underlain by permafrost (Viereck and Johnston 1990). The natural disturbance regime is one of large catastrophic fires that can consume several thousand ha of forest, followed by natural regeneration. Although fire has historically been the primary disturbance factor in these black spruce forests, over the past thirty years, tree harvesting has become a greater disturbance factor in some forest sectors. In central Quebec, 100,000 ha of black spruce forests are harvested annually (Prévost 1997). Thus, the disturbance regime has been shifting from periodic (50 to 150 year interval; Bergeron et al 1996) large-scale fire to large-scale clearcutting (or CPRS) every 80 to 100 years, the planned rotation age. Despite this increase in harvesting intensity, this ecosystem's structure, function, and response to disturbance is currently not well understood.

Certification of forestry activities or adoption of sustainable forest management will require as one criteria the demonstration that ecosystem functions and forest productivity are maintained or enhanced in the long term. The productivity of the forest depends in part on site resources – nutrients, water, light – that are available for tree growth. The cool, humid climate associated with the black spruce forests of Québec contributes to accumulation of the surface organic humus of the soil, which may result in cooler soil temperatures and reduced availability of nutrients to trees. The effect of the natural disturbance of fire is to periodically burn off a certain thickness of the surface humus, at the same time stimulating nutrient availability for some years after the fire. Do current harvesting practices mimic the natural disturbance? In Quebec, the use of CPRS (cut protecting regeneration and soils) is encouraged by the provincial government to protect natural regeneration (trees < 10 cm diameter) and to eliminate costly artificial regeneration. This practice is applied widely where advanced regeneration indicates sufficient pre-harvest stocking. It protects the natural regeneration that is already established on the site, but minimises disturbance of the soil.

Our major question is: if we do not reduce the depth of organic matter and stimulate nutrient availability using this practice, will seedling and advanced regeneration and growth be hindered by a lack of nutrient resources? To answer this question we are evaluating soil fertility (both short term nutrient availability and soil reserves of nutrients), seedling regeneration and longer term tree growth in both young (5 to 10 years old) and older black spruce stands (> 50 years), on the oldest available harvested sites in the Chibougamau region of Quebec. We are also examining the potential impact of increased ericaceous vegetation on nutrient availability, by manipulating chemistry of the forest floor. Results of our study will be contribute to a modelling effort to improve predictions of site productivity response to a wide range of natural and harvest/silviculture related disturbances.

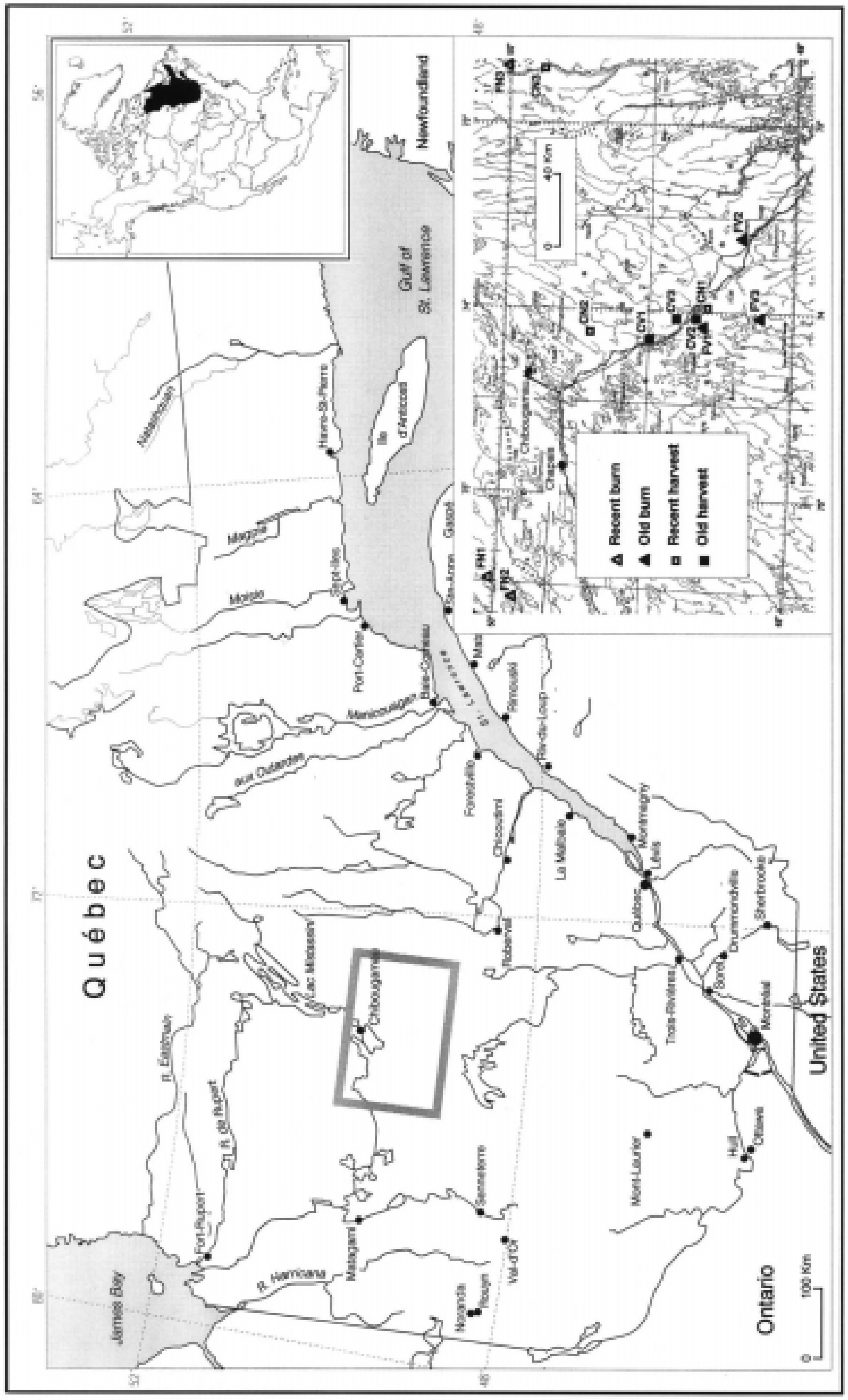
The present report will outline progress to date in the project, presenting results from laboratory incubations of soil, field studies of soil fertility and a bioassay on young and older sites, and growth analyses of trees on the six older sites. Management implications will be discussed and finally, conclusions. Current work to complete the project in 1999-00 and products will be outlined.

METHODS

General Methods and Chronology

Funding for the initial stages of the project was received in 1996, and the project was placed into the Network's Ecological Basis of Sustainable Forestry Theme (Stand Dynamics Group), since then transferred under Soils and Regeneration groups to address Legacies 1) 2) and 3). We wanted to address two of the Canadian Council of Forest Minister's criteria and indicators of sustainable forest management which included: 1) the maintenance and enhancement of forest ecosystem condition and productivity and 2) the conservation of soil and water resources. The initial general hypothesis of the project was that the treatment of CPRS created ecological conditions (i.e., stand function and structure) that were significantly different from conditions that result from natural perturbation in black spruce ecosystems. To address this hypothesis, twelve permanent plots were established in the Chibougamau - Lac St. Jean region of central Quebec (Figure 1), with three plots (50 x 50 m^2 in non-contiguous stands) located in each disturbance type (recently burned, recently harvested with CPRS, old burn, old harvest). The field season of 1996 was dominated by site selection, plot establishment, the installation of dataloggers to measure microclimate in each of the disturbance types, the collection and analysis of soil samples, and surveys of vegetation and stand characteristics at each of the experimental sites.

In the winter and spring of 1997, we conducted laboratory incubations with the organic layers and mineral soils collected from the recently burned, recently harvested, and old harvest sites. The objective of this study was to examine the release of organic and inorganic forms of nitrogen (N) and phosphorus (P) and their relationship with CO_2-C efflux. We also completed a detailed analysis of the nutrient and carbon contents of mineral soil and organic horizons that were collected in the fall of 1996. During the field season of 1997 (June 1 - October 1), we completed several activities, all which were designed to identify differences in site productivity between the four disturbance types. These activities included the following: 1) daily observations of soil and air temperatures and soil moisture with the dataloggers that were installed in 1996, 2) monthly field incubations to estimated organic and inorganic-P and -N dynamics in soils, 3) monthly estimates of soil microbial biomass-C and -N, 4) the planting of seedling bioassays to examine their response to the microclimate and nutrient availabilities in the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Port-Cartier
Sept-Îles
Havre-St-Pierre
Gaspé
Manicouagan
aux Outardes
Moisie
Magpie
Natashquan
Chapais
100 Km
40 Km
Recent burn
Old burn
Recent harvest
Old harvest

recently burned and harvested sites, and 5) the estimation of fine root biomass and length in the four disturbance types.

During the field season of 1998 (May 15- October 15), we completed the following activities: 1) the collection of microclimatological data from each of the disturbance types, 2) the installation and collection of fine root ingrowth cores, 3) the estimation of soil CO_2-C efflux from the recently disturbed sites, and 4) the 2nd year harvest of the seedling bioassays. We are currently analyzing data from the ingrowth cores and 2nd year bioassay.

In 1998, our project was more formally integrated with projects in Alberta and Quebec, working with W.McGill and J.Offord at the U. of Alberta, as well as P. Rochon and D. Paré at UQAM. The objective of this integration was to use field data collected in Alberta and Quebec to calibrate, evaluate, and adapt existing models to better predict long-term site productivity in disturbed sites.

Brief Description of Methods

Laboratory Incubations

In August 1996, three transects were established in each of the nine stands, and ten samples of the surface organic layer (F, H horizons) and of the surface soil (0 to 10 cm depth) were taken at five m intervals in each transect. Samples were sealed in a plastic bag at field moisture contents and frozen at –20°C until February 1997. For each replicate (stand), we incubated two composite samples from the forest floor (i.e., 2 samples x 3 replications x 3 disturbance types = 18 total samples) and three composite samples from the mineral soil (i.e., 3 samples x 3 replications x 3 disturbance types = 27 total samples) for 84 days. Thawed samples were placed in 150 ml filtration units with filters and acid-washed silica sand. The humus and mineral soil samples were incubated at 13°C, which is similar to the maximum average temperatures recorded in black spruce forest floors and mineral soils in central Quebec during the growing season (Prévost, 1996). Leachings of the soil were conducted every seven days for 84 days to determine release of ammonium, nitrate, phosphorus and organic nitrogen and phosphorus. Carbon dioxide release from the forest floor and soil samples was also estimated every seven days. More detailed methods are presented in Smith et al. (1998).

Field Studies of Soil Fertility

In August 1996, three transects were established in each of the twelve stands, and ten samples of the surface organic layer (L, F, and H horizons) and of the surface soil (0 to 10 cm depth) were taken at five meter intervals in each transect. Samples were sealed in a plastic bag at field moisture content and frozen at -20°C until analysis. Initial mineral and organic soil samples were analyzed for organic matter, total C, N and P (Smith et al.1999). The pH and bulk density of all the initial samples was also determined. Soil C, N, and P stocks were calculated using element concentrations, soil bulk density, and the soil sampling depth.

Monthly net N mineralization and nitrification were estimated *in situ* from early June to late September 1997 using a revised version of DiStefano and Gholz's (1986) methodology. In each experimental plot (4 disturbance types x 3 replicates = 12 plots total), 4 polyvinylchloride (PVC) tubes 10 cm long and 5 cm wide (inner diameter) were filled with organic material (L, F, and H horizons combined) or mineral soil (0 to 10 cm depth) that was removed from four random locations. Four tubes were randomly placed in each plot per month; thus each month, 48 tubes were processed. Time-zero soil samples were taken from the same soil sample that was placed in the tube, for determination of inorganic and organic N and P. The tubes were removed from the ground after 24 to 28 days, and soils and resins were extracted again for inorganic and organic N and P, as well as microbial biomass C and N.

Soil and air temperatures were recorded in one replicate of each of the four disturbance types using dataloggers (CR10X, Campbell Scientific, Inc.) from June 3 to September 26, 1997 and June to September, 1998. Daily maximum, minimum, and average soil temperatures were obtained based on sampling every minute with thermistors installed 11 meters from the center of each plot in three directions (N, SE, NW). The thermistors were placed at a 5 cm depth in the organic horizons and a 10 cm depth in mineral soil. Daily maximum, minimum, and average air temperatures were monitored at 1.5 meters above the forest floor. Organic horizon and mineral soil moistures were measured gravimetrically from the 48 samples collected each month for the N mineralization study.

To better understand which ecosystem component dominated fine root C, N, and P storage in each disturbance type, we sampled for fine roots (< 2 mm diameter) in the organic horizon of each stand during the last week of September 1997. We collected fine roots in three random transects per replicate plot, and by taking seven cores (5 cm diameter) of the organic horizon (to the mineral soil) at 4 m intervals in each transect. Thus, we took 21 cores per replicate plot x 3 replicate plots x 4 disturbance types = 252 total. Fine roots were manually separated from the organic material and divided into two groups; ericaceous plus herbaceous roots (primarily ericaceous) and conifer roots (primarily black spruce). While the samples were fresh, the total length of live fine roots in each core was estimated. Total C, N and P in the fine roots were determined by chemical analyses (Smith et al. 1999).

Seedling Bioassay

Black spruce nursery stock from the St. Felicien nursery in the Lac St. Jean region were planted out on the six young sites (3 burns, 3 harvested sites) in June, 1997. Seedlings were planted in 10 series of 5 per site; on the CPRS sites, series were established on both skid trail and between skid trail microsites, to compare performance under these different conditions. Tens seedlings were harvested per site in each of September 1997 and 1998, measured for growth parameters, and biomass allocation. Nutrient analyses of current needles was also carried out.

Growth Analysis of Older Stands

Six sites were chosen for longer term growth studies : three fire sites dating from 1919 to 1929, and three cut sites (harvested by horse logging in winter) dating from 1939 to 1949. Sites were chosen with similar ecological characteristics; soil drainage (mesic), texture (sandy loam to loamy sand), and topography (slope) were kept constant to allow a comparison of disturbance type without confounding site factors.

Three circular plots of $400m^2$ were established at each site, including one in the inside the permanent main plot used for soil fertility studies. Competition cells were then established in one of the three plots for studies of spatial structure in relation to growth. The number of stems per plot was counted and height and diameter were measured on 15 trees per plot (45 per site). Basal area was determined from diameter. Age was determined on these same 15 trees, from cores or stem analysis. To determine spatial structure, LAI (leaf area index) was determined for a group of trees, using both measures of distance between trees, and evaluation of leaf area index of individual trees, using the random branch sampling method.

For stem analysis studies, five trees were chosen in one competition cell. Height was measured and three disks were taken from each tree : one at the base of the stem, one at breast height (dbh) and one at the base of the live crown. Windendro TM software was used to analyse diameter increments in the disks and height and volume increments were estimated using Anatige TM software. The relationship between dbh and volume of trees was established for cut sites and fire origin sites, to estimate volume per plot and hence, volume per ha. The volume of study trees at a common age 50 was also estimated, to allow more valid comparisons of the two types of disturbance.

IMPORTANT RESULTS

Temperature and moisture

From June 1 to October 1, 1997, minimum daily air temperatures were lower than freezing (0°C) thirteen times in the recently burned and harvested stands, but only three times in the old burn and old harvest stands (Smith et al. 1999). The highest air temperature recorded was 35°C in the recent burn during late July. The highest average temperatures in the organic horizons were reached in late July and ranged from 12°C (old harvest) to 14°C (recent burn). The highest temperatures in the mineral soil were reached in early August and ranged from 10°C (old harvest) to 12°C (recent burn). The first season of data suggests that the old cut site has the coldest temperatures at the beginning of the growing season, while the recent fire site is warmest during most of the season. Soil and air temperatures were also recorded in the growing season of 1998, and during the fall and winter 1998-99. Data are currently being analysed.

Soil carbon and nutrient stocks

Soil C, N, and P stocks were calculated using element concentrations, soil bulk density, and the soil sampling depth (Smith et al. 1999). Wildfire and tree harvesting can alter the masses of the surface organic horizon and surface mineral soils, therefore we first estimated the unadjusted C, N, and P stocks in the organic horizon and surface mineral soil using the depths and bulk densities reported in Table 1. We then estimated the adjusted C, N, and P stocks in the organic horizon and surface soils using Ellert and Bettany's (1995) technique for calculating element masses in an equivalent soil mass (Table 1). Since the soil bulk densities and element concentrations were vastly different between the surface organic horizon and the mineral soil in each disturbance type, we analyzed the two horizons separately.

The recently burned stands had the shallowest organic horizon with the lowest bulk density (Table 1). The recently burned stands had the lowest unadjusted C stocks in the organic horizon, but after estimating the elemental masses based on equivalent soil masses, this disturbance type had higher mean C stocks compared to the recently harvested sites (Table 2). The recently harvested sites had unadjusted C and N stocks that were intermediate between the recent burn and older disturbance types (Table 1). After the adjustment for equivalent soil masses, these stands had the lowest mean N and P stocks (organic horizon) of all the disturbance types (Table 1). There were no differences among the disturbance types for adjusted C, N, or P stocks in the organic horizon (P = 0.79, 0.54, and 0.40, respectively). In the surface mineral soils, the recently burned and old harvest stands had the lowest bulk densities (Table 1). The older disturbance types had higher adjusted C and N stocks compared to the recently disturbed sites (Table 1), and there were significant differences among the disturbance types for the adjusted N stocks in mineral soil (P = 0.06).

Table 1. The depth, bulk density, and adjusted soil C, N, and P stocks in the four disturbance types in central Quebec (Smith et al. 1998a).

Disturbance Type	Depth (cm)	Bulk Density (g/cm3)	C (kg/m2)	N (g/m2)	P (g/m2)
		Organic Horizon			
Recent Burn	7.9 (0.9)	0.11 (0.002)	5.4 (0.2)	142.2 (9.1)	12.1 (2.3)
Recent Harvest	10.2 (1.4)	0.12 (0.01)	5.2 (0.5)	125.3 (6.4)	8.5 (0.6)
Old Burn	10.7 (1.2)	0.13 (0.007)	5.0 (0.8)	145.8 (18.6)	9.5 (0.8)
Old Harvest	11.5 (0.7)	0.12 (0.01)	5.2 (0.5)	144.7 (16.8)	8.7 (0.7)
		Mineral Soil			
Recent Burn	0 - 10	1.17 (0.04)	2.2 (0.3)	85.1 (13.5)ab	4.0 (1.1)
Recent Harvest	0 - 10	1.32 (0.21)	2.2 (0.3)	75.9 (4.2)b	6.0 (1.9)
Old Burn	0 - 10	1.40 (0.19)	3.0 (1.0)	113.9 (12.5)a	3.5 (1.4)
Old Harvest	0 - 10	1.18 (0.10)	3.2 (0.4)	106.0 (10.8)ab	6.2 (0.6)

Soil N and P dynamics

In the laboratory incubations, there was a large initial release of dissolved organic nitrogen (DON), and the cumulative concentrations of DON ranged from 7 to 17% and 31 to 45% of total N extracted from the organic horizons and mineral soils, respectively (Smith et al. 1998). Cumulative concentrations of dissolved organic phosphorus (DOP) ranged from 35 to 48% of total P extracted from the organic horizons and mineral soils, and we detected a pulse of CO_2-C release from the organic material after thawing. These results suggested that there is a pulse of microbial activity in soils after the spring thaw and that DON and DOP are an important part of N and P cycling in these systems.

In the field incubations, the highest net production rates of inorganic and organic sources of N and P were for NH_4^+-N, and the old burn and harvest sites had higher net inorganic-N production compared to the recently disturbed sites (Table 2). These differences were attributed to the higher availabilities of DON in the older sites throughout the growing season (Smith et al. 1999). In contrast to the N dynamics, extractable inorganic-P concentrations were much higher than DOP concentrations in all the disturbance types.

Table 2. Total net production (± SE) of inorganic- and dissolved organic-N and -P in the organic horizon and surface mineral soils (0 to 10 cm depth) of the four black spruce disturbance types from June 3 to September 26, 1997 (115 days).

Disturbance Type	NH_4^+-N	NO_3^--N	DON	PO_4^{-3}-P	DOP
		Net production (kg/ha) in organic horizon			
Recent burn	3.7 (2.0)b	0.01 (0.07)	-0.38 (0.2)	0.24 (0.1)	-0.01(0.01)
Recent harvest	3.4 (2.2)b	-0.06 (0.8)	-1.23 (0.7)	0.48 (0.5)	0.28 (0.3)
Old burn	13.3 (2.3)a	-0.02(0.09)	-2.84 (2.1)	1.46 (1.5)	0.44 (0.2)
Old harvest	17.2 (3.1)a	-0.14 (0.2)	-1.44 (1.1)	2.30 (0.7)	-0.05 (.05)
		Net production (kg/ha) in surface mineral soils			
Recent burn	0.10 (1.7)	1.45 (1.8)	ND	0.15 (0.1)	ND
Recent harvest	3.86 (3.6)	0.03 (0.2)	ND	0.10 (0.06)	ND
Old burn	3.67 (2.9)	-0.12 (0.2)	ND	-0.47 (0.1)	ND
Old harvest	5.66 (2.4)	-0.13 (0.2)	ND	0.06 (0.2)	ND

Note: ND = no data. The columns where mean values are followed by different letters indicates where there were significant differences among the disturbance types ($P < 0.10$, Tukey's HSD of rank transformed data, $n = 3$).

Seedling bioassays, microbial biomass-C and -N, and soil CO_2-C efflux

The data collected from the seedling bioassays, analysis of seasonal changes in soil microbial biomass-C and -N, and our estimates of soil CO_2-C efflux are currently being analyzed. For the seedling bioassays, our first-year analysis of seedlings that were planted in the recently burned and recently harvested sites indicated that there were no significant differences in N, P, or C contents in seedling tissues planted in each disturbance type. In the CPRS sites, the seedlings planted in the non-disturbed rows (where the tree harvester didn't disturb the organic layer) had significantly higher P contents in 1st and 2nd year needles.

In the organic horizons, there was a tendency for mean microbial biomass-C to be highest in the recently burned sites in early June 1997 (1400 μg C g^{-1}), but as the summer progressed, mean estimates of biomass-C were almost equal for all the disturbance types (2500 - 3000 μg C g^{-1}) until late September. Microbial biomass-N in the organic horizons ranged from 62.5 to 120.3 ug N g-1 in June (old harvest and recent burn, respectively), and 152.4 to 605.1 ug N g-1 in September (old harvest and recent harvest. respectively).

Soil CO_2-C efflux was measured during daytime hours in two sites (one recently burned, one recently harvested) from May to September 1998. In mid-May 1998, CO_2-C efflux was higher in the recently harvested site (1.9 - 2.9 μmol CO_2 m^2 s^{-1}) compared to the recently burned site (1.9 - 2.1 μmol CO_2 m^2 s^{-1}). We are currently analyzing the measurements taken from July to September 1998.

Fine root carbon and nutrient stocks

Conifer fine root (< 2 mm diameter) length and biomass was low in soils of the recently disturbed sites which were dominated by ericaceous shrubs (Table 3). In contrast, conifer fine root length and biomass in the older disturbance types was higher than that for the ericaceous shrubs. The older disturbance types had higher N contents in fine root biomass compared to the recently disturbed sites ($p < 0.1$), but there were no differences among the disturbance types for fine root C and P contents (Smith et al. 1998a).

Table 3. Fine root (0 - 2 mm diameter) biomass (ash free) and length (± 1 SE) in the surface organic horizons from the four black spruce disturbance types (Smith et al. 1999).

Disturbance Type	Biomass (g/m2)	Length (m/m2) Ericaceous*	Conifer*	Total
Recent Burn	170.4 (31.6)a	1029.6 (177.4)a	30.9 (5.1)d	1060.6 (176.6)ab
Recent Harvest	175.6 (33.1)a	1136.3 (188.2)a	87.6 (21.5)c	1224.0 (168.2)ab
Old Burn	241.7 (47.2)a	195.7 (54.5)b	721.3 (62.7)b	917.0 (33.9)b
Old Harvest	321.8 (48.4)a	704.0 (160.6)ab	918.6 (37.5)a	1622.7 (170.0)a

*Note: We divided the fine root length into two classifications: an ericaceous class which is made of primarily *Ledum*, *Kalmia*, and *Vaccinium* (but which also included small amounts of herb and forb roots), and a conifer class that was primarily black spruce roots (but also included balsam fir and jack pine roots). In each column, mean values followed by different letters indicates significant differences among the disturbance types (Tukey's HSD of rank transformed data, $p < 0.10$, $n = 3$). Fine root biomass was estimated for live and dead roots, fine root length was estimated for live roots.

Growth analysis of older stands

Stands that originated from logging were more variable than those originating from logging. Part of the differences in height and average diameter at breast height can be attributed to age differences (Table 1). However, the structure of second growth (harvested) stands was more irregular (trees were grouped) so that local leaf area was higher in the clumps of layers even though stand density was lower. Clearings in these stands were occupied by ericaceous shrubs (Figure 2).

Table 1. Characteristics of the study stands

Stand origin	Year of disturbance	Density (stems/ha)	Basal area (m^2/ha)	Height (m)	Average dbh (cm)
Fire	1906	2142	42,1	15,1	15,1
	1918	3984	42,2	12,4	11,1
	1919	2983	49,1	14,2	13,8
Logging	1942	2642	29,8	10,8	11,1
	1942	2475	18,4	9,6	9,3
	1947	2442	30,4	11,1	11,7

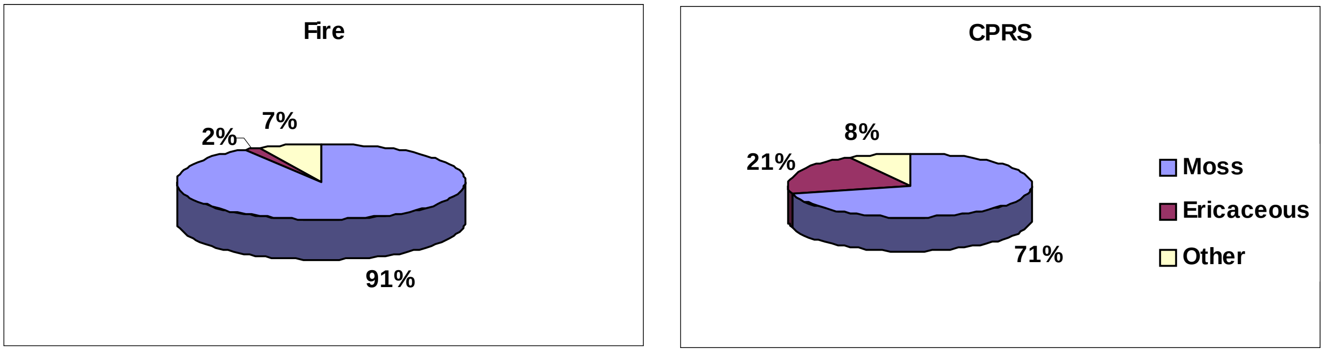

Figure 2. Percent cover of moss, ericaceous species and other species (herbaceous and grasses) after fire and after harvest (CPRS).

Growth analysis at the tree level was able to identify changes in growth patterns. For a similar height, growth was inferior in stands that originated from logging (Figure 3). The competition taking place in both stand types was also very different. Even when growth was compared for similar competition indices that took into account the relative size of the subject tree and its competitors, as well as the distance between their crowns, differences in volume growth remained. Hence, volume growth for a similar level of competition was inferior for stands that originated from logging (Figure 4).

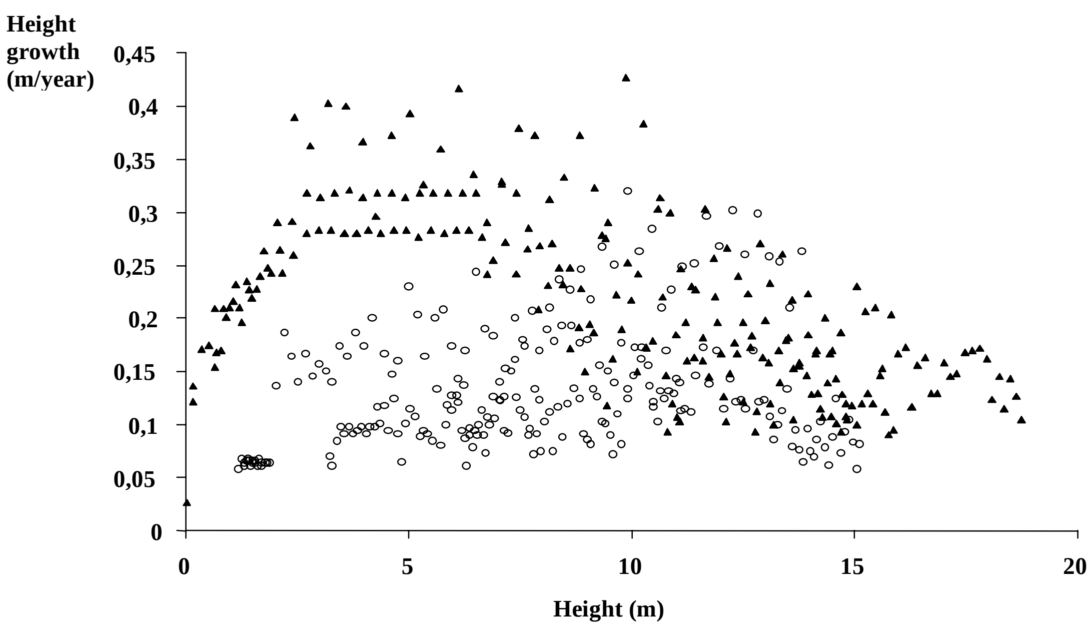

Figure 3. Growth comparison of stands originating from fire (filled symbol) and logging (open)

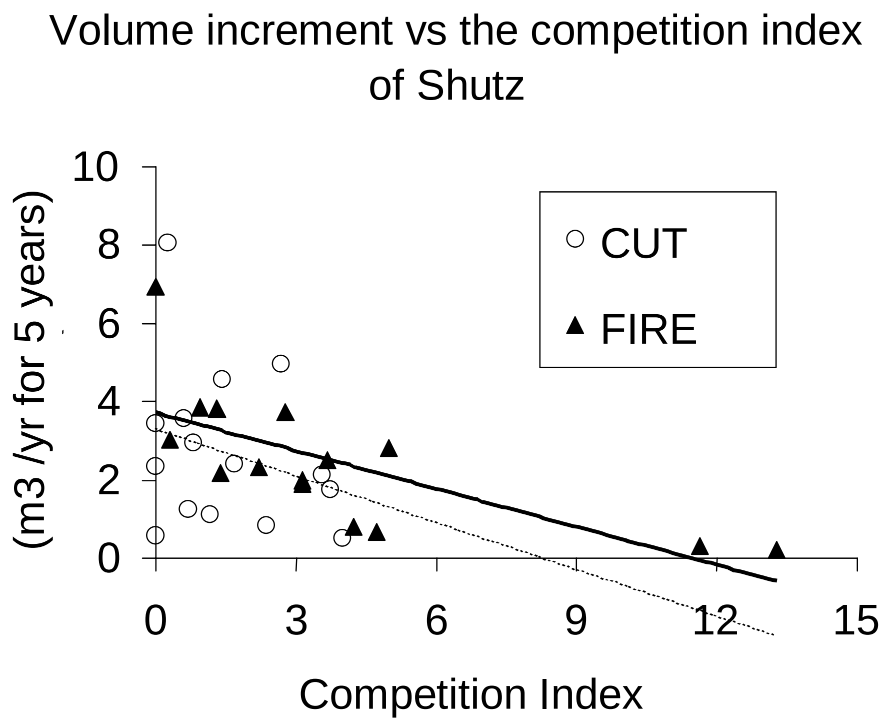

Figure 4. Volume increment as a function of competition index for stands originating from fire and logging.

Acceptable yields have been found elsewhere for a first rotation after logging (Lussier, 1997; Pothier et al. 1993; Paquin and Doucet 1992). However, these yields are largely dependant on the size advantage of the advance growth. The present study indicates that changes in growth processes are occurring and that these changes could compromise the future yield of those stands. These changes could be related to modifications in resource use between trees and ericaceous shrubs. Soil temperature and decomposition/mineralization under groups of layers could also be reduced, leading to a growth reduction. The present study has also observed differences in growth allocation between the different parts of the tree. These differences could reflect a less efficient use of photosynthates for stem biomass increment.

IMPLICATIONS FOR MANAGEMENT

Across the globe, as the largest remaining tracts of previously unmanaged forest become disturbed by human activity, there is increasing interest concerning the effects of anthropogenic disturbances on soil C, N, and P stores because forest soils are generally the largest ecosystem stocks for these three elements (Schlesinger 1986). Until modern times, fire and insect outbreaks were the major forms of forest disturbance in Quebec’s forests, but in 1995, the land area harvested (357,443 ha) vastly exceeded the area burned by wildfire (195,600 ha, Canadian Council of Forest Ministers, 1997). In the upland black spruce forests of Quebec, 89 and 90% of ecosystem N and P are found in the forest floor and mineral soils (Weetman and Webber 1972), therefore, as tree harvesting becomes an increasingly important agent of disturbance throughout the North American boreal forest, understanding the short and long term changes of C, N, and P stocks and dynamics caused by fire and harvesting are important to understand.

In our four disturbance types in central Quebec, adjusted soil C and N stocks (organic horizon + surface mineral soil) in the recently disturbed sites were 5 to 22% lower compared to the sites disturbed 56 to 76 years ago. The adjusted C, N, and P stocks in the recently harvested sites were 2 to 11% lower than in sites recently burned by wildfire. Thus, in the short-term, black spruce stands that were disturbed by the CPRS harvesting method experienced a decrease in soil C, N, and P stocks compared to sites that were burned by wildfire. In the older disturbance types, total adjusted soil C and N stocks varied by only 3 to 4%, suggesting that despite initial differences in soil properties after fire and harvesting, soil C and N stocks appear to recover after the first harvest. In the future, it will be important to compare burned stands with sites that have experienced several rotations of biomass removals to determine if C and N stocks return to similar levels after repeated harvesting. Also, in these black spruce sites, calcium (Ca) stores in aboveground vegetation are much higher than stores in the soils (Weetman and Webber 1972), thus repeated biomass removals may reduce soil Ca stocks to critical levels. In central Quebec, soil Ca and Mg limits the growth of black spruce seedlings planted in harvested sites (Paquin et al. 1998), indicating that changes in soil Ca and Mg stocks and availabilities will be important to consider in future work.

Ericaceous species are an important component of these black spruce ecosystems, and our results demonstrate their dominance in the younger stands, both after harvest and after fire. Data for both vegetation cover and fine root biomass and length indicate an increased presence of these species (*Ledum, Kalmia and Vaccinium* spp.) after harvest compared to after fire. This increased presence could have serious consequences for both stocking and productivity of sites. Experience in Newfoundland has shown inhibition by *Kalmia* of black spruce germination (Titus et al. 1995), and in Quebec, Yamasaki observed poor nutrition of balck spruce and inhibition of mycorrhizal fungi in association with ericaceous spp. (Yamasaki et al. 1998). From Newfoundland experience again, we know that these species are very difficult to control once established on a site (Titus et al. 1995). Only high rates of herbicide or deep scarification have shown any success, and Quebec will lose widespread use of herbicide by the year 2001. If we lose an important area due to increases in ericaceous species on black spruce sites, implications for loss in volume could be important. The results suggest we need to look at the impacts of CPRS more closely.

Horvath`s study of longer term growth also supports the latter statement. The study indicates a very different spatial structure of stands after harvest, where there is a strong grouping of trees with high variability in leaf surface area within the groups. Trees growing within this kind of clumped structure allocated less biomass to stems and more to branches. Nutrition tended to be lower on the harvested sites (esp. nitrogen and calcium). The present study, to be completed in 1999, indicates that changes in growth processes are occurring and that these changes could compromise the future yield of these stands. These changes could be related to modifications in resource use between trees and ericaceous shrubs. Soil temperature and decomposition/ mineralization under groups of layers could also be reduced, leading to a growth reduction.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

1. Soils after harvest appear to be colder, even though the depth of organic matter was not significantly different in older stands (CPRS versus fire). The light regime and tight grouping of trees after harvest might be responsible for this effect. We are continuing to monitor soil temperature over a longer time period.

2. The study of soil fertility does not indicate major impacts of harvest (CPRS) on soil nutrient reserves, in comparison to the impacts of natural disturbance of fire. However, we need to continue to monitor these impacts in the long term and over rotations.

3. Soil nutrient availability is unexpectedly higher in older versus younger stands, but again, there is not a significant difference between disturbance types, in either the younger or older stands. The low nutrient availability on the younger sites (6-10 years after disturbance) may be related to the dominance of ericaceous shrubs at this stage of succession. Organic forms of nitrogen (DON) appear to be an important component of the N cycle in these ecosystems.

4. For a similar height, growth (height increment) was inferior in stands that originated from logging (CPRS) compared to fire. As well, volume growth for a similar level of competition was inferior for stands that originated from logging. Previous studies have not shown this lower growth for harvested stands; it indicates that for prediction of future volume, we may need to analyse a larger number of logged stands to have reliable information.

5. The structure of CPRS stands (with frequent gaps) appears to encourage greater establishment of ericaceous species (*Ledum, Kalmia, Vaccinium* spp.). Once established, these species are very difficult to eradicate in future rotations, which may reduce stocking and growth in the long term. We need to look at this particular problem to understand if it is important on a large scale in Quebec.

6. To prevent increases in ericaceous species presence, and colder soil temperatures, which may reduce nutrition of trees, it may be necessary to implement a program of scarification (intensive) on potentially problem sites, identified to have an important presence of ericaceous species before harvest.

CURRENT AND FUTURE WORK

In the last year of this project, we are completing soil respiration and microbial biomass measures in the field, as well as collecting litter for evaluation of litter quality. We are also evaluating more closely the impact of *Kalmia angustifolia* on black spruce seedlings, both in the field and in a controlled greenhouse study. All field work for the long term growth study is completed and results will be synthesized in the thesis of Robert Horvath, for the autumn of 1999. Our project will also continue to focus on the collaboration with Drs. Bill McGill and David Paré and our efforts to calibrate, evaluate, and adapt existing models to better predict soil nutrient availability and long-term site productivity in disturbed sites throughout Canada's boreal forests. This integration project and modelling exercise will also be completed in 1999-00.

Our studies suggest that the both potentially reduced yields after CPRS and the potential for ericaceous species expansion on harvested black spruce sites warrants further attention in Quebec. For the latter problem, a short term investigation of ericaceous species on a large number of harvested sites in the region of Lac St-Jean would identify whether there is a problem on a wider scale across this black spruce forest. We know that this has been identified as a problem for regeneration and growth of black spruce on north shore sites (Jobidon, personal communication). Our group aims to continue to evaluate this problem and its consequences with both fundamental and applied studies.

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